Design, Simulation and Verification of Generalized Photovoltaic cells Model Using First Principles Modeling

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***Abstract*—This paper presents the implementation of a generalized photovoltaic model of PV cell, module, and array model applicable for mono crystalline, poly crystalline silicon, thin film like CIS, CdTe, Amorphous silicon, polymer from various manufacturers on Matlab/Simulink simulation software platform using first principle method. This model is known to have better accuracy estimation of electrical behavior of the cell with respect to changes on environmental parameter of temperature and irradiance. All inputs to the model can be easily extracted from standard PV module datasheet. The functioning of the proposed model is evaluated by simulation. The accuracy of the simulation is verified by comparing output current and power characteristics of PV cell with datasheet provided by PV cell manufacturers.**

***Index Terms*— pv modeling, mono-crystalline, multi-crystalline, pv module, STC, thin-film, matlab, simulink**

I. Introduction

Recently, PV systems have received a great deal of attention due to the exhaustion of energy sources, high oil prices and environmental pollution. The World Energy Forum has predicted that fossil based oil, coal and gas reserves will be exhausted in less than another 10 decades. Fossil fuels account for over 79% of the primary energy consumed in the world, and 57.7% of that amount is used in the transport sector and are diminishing rapidly. This results in 40% of carbon footprint across the globe.

The amount of incoming solar energy in one year is equivalent to fifty times the known reserves of coal, 800 times the known oil reserves. A PV system directly converts solar energy into electric energy. A powerful attraction of PV systems is that they produce electric power without harming the environment, by directly transforming a free inexhaustible source of energy, solar radiation, into electricity. This fact, together with the continuing decrease in PV arrays cost (tenfold in the last two decades) and the increase in their efficiency (threefold over the same period). Commercial Photovoltaic cells were first developed in Bell lab in 1954 with 6% efficiency. But, only after their use in space programs in 1950's commercial interest surged up. Since then interest in their use in various applications like power supplies to residential appliances, grid connected solar inverter, telecommunications, refrigeration and water pumping. In PV power generation, due to the high cost of modules, optimal utilization of the available solar energy has to be ensured. Also PV system requires special design considerations due to the varying nature of the solar power resulting from unpredictable and sudden changes in weather conditions, which change the radiation level as well as the cell operating temperature. This mandates an accurate and reliable simulation of designed PV systems prior to installation.

II. Photovoltaic cell

Solar cells consist of a p-n junction fabricated in a thin wafer or layer of semiconductor. In the dark, the I-V output characteristic of a solar cell has an exponential characteristic similar to that of a diode.

When exposed to light, photons with energy greater than the bandgap energy 'E_g' of the semiconductor are absorbed and create an electron-hole pair. These carriers are swept apart under the influence of the internal electric fields of the p-n junction and create a current proportional to the incident radiation. When the cell is short circuited, this current flows in the external circuit; when open circuited, this current is shunted internally by the intrinsic p-n junction diode. The characteristics of this diode therefore set the open circuit voltage characteristics of the cell.

III. Modelling the solar cell

The simplest equivalent circuit of a solar cell is an ideal current source in parallel with a diode [1-4]. The current source represents the current generated by photons (often denoted as I_{ph}), and its output is constant under constant temperature and constant incident radiation of light. The diode determines the I-V characteristics of the cell.

Increasing sophistication, accuracy and complexity can be introduced to the model by adding in turn.

- Temperature dependence of the diode saturation current.
- Saturation current contribution due to diffusion process.
- Saturation current contribution due to recombination in the space charge layer effect dominant at higher bias region.

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- In small size solar cells leakage current has an effect on the low bias region.
- Temperature dependence of the photo current I_{ph}.
- Shunt resistance R_p in parallel with the diode [11-15].
- Series resistance R_s, which gives a more accurate shape between the maximum power point and the open circuit voltage [5-10].
- Either allowing the diode quality factor *A* to become a variable parameter (instead of being fixed at either 1 or 2) or introducing two parallel diodes (one with *A* = 1, one with *A* = 2) with independently set saturation currents.

The single exponential model or the double exponential model usually represents the PV panel. The single and the double exponential model are shown in Fig. 1 and 2 respectively. The current is expressed in terms of voltage, current and temperature as shown in (1).

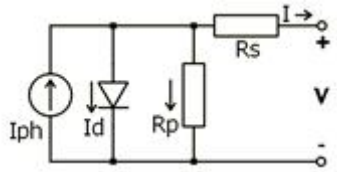

Figure 1. Single exponential model of a PV Cell

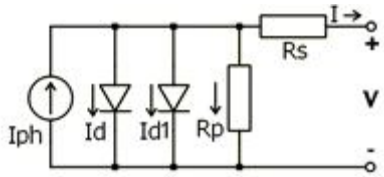

Figure 2. Double exponential model of PV Cell

For this research work, three different types of model staring from simplicity to complexity were used.
Type1: Single diode model with Rs neglecting Rp.
Type2: Single diode model with Rs and Rp.
Type3: Complex Double diode model with Rs and Rp

A. Current-Voltage I-V Curve for a Solar Cell

Fig. 3 shows the I-V characteristic curve of a solar cell for certain irradiance 'G' at a fixed cell temperature 'T'. The current from a PV cell depends on the external voltage applied and the amount of sunlight on the cell When the cell is short-circuited, the current is at maximum (short-circuit current 'I_{sc}'), and the voltage across the cell in open circuit condition is at its maximum (open circuit voltage 'V_{oc}'), and the current is '0'.

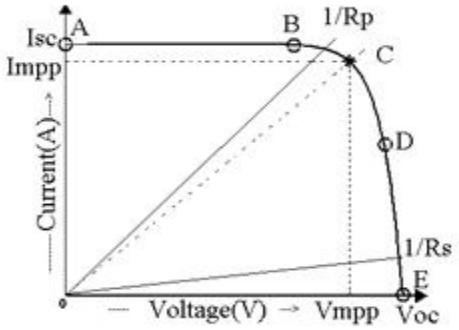

Figure 3. A typical Current voltage I-V curve for photovoltaic cells

If the cell's terminals are connected to a variable resistance, *R*, the operating point is determined by the intersection of the *I-V* characteristic of the solar cell with the load *I-V* characteristics. As shown in Fig. 3 for a resistive load, the load characteristic is a straight line with a slope I/V = 1/R. If the load resistance is small, the cell operates in the region *AB* of the curve, where the cell behaves as a constant current source, almost equal to the short circuit current. On the other hand, if the load resistance is large, the cell operates on the region *DE* of the curve, where the cell behaves more as a constant voltage source, almost equal to the open circuit voltage [16]. Point *C* on Fig. 3 is also called the maximum power point, which is the operating point (P_{max}) at which the output power is maximized. The model included temperature dependence of the photocurrent I_{ph} and the saturation current of the diode I_o. Diode quality factor 'A' set to achieve the best curve match. The circuit diagram for the solar cell is shown in Fig. 1 and 2.

B. Type-1 PV Model

The equations, which describe the I-V characteristics of Type1, are

$$I = I_{ph} - I_o\left[\exp\left(\frac{q\cdot\left(V + IR_s\right)}{AkT}\right) - 1\right] \quad (1)$$

where, *I* is the PV array output current (A); *V* is the PV array output voltage (V); *q* is the charge of an electron; *k* is Boltzmann's constant; *A* is the p-n junction quality/ideality factor; *T* is the cell temperature (K); and I_o is the cell reverse saturation current. The factor '*A*' in (1) determines the cell deviation from the ideal p-n junction characteristics; it ranges between 1 and 2, 1 being the ideal value.

The value of R_s was calculated by evaluating the slope dI/dV of the I-V curve at the V_{oc}. The equation for R_s was derived by differentiating the I-V equation and then rearranging it in terms of R_s [17-18].

$$R_s = -\left|\frac{dV}{dI}\right|_{V_{oc}} - \frac{1}{\frac{q\cdot I_o}{AkT}\exp\left(\frac{qV_{oc}}{AkT}\right)} \quad (2)$$

Where, dV/dI is the slope of the I-V curve at the Voc. The cell reverse saturation current I_o varies with temperature according to the following equation [19-20].

$$I_o = I_{or}\left[\frac{T}{T_r}\right]^{\frac{3}{A}}\exp\left(\frac{qE_g}{Ak}\left[\frac{1}{T_r} - \frac{1}{T}\right]\right) \quad (3)$$

where, T_r is the cell reference temperature, I_{or} is the reverse saturation current at T_r and E_g is the band-gap energy of the semiconductor used in the cell. The photocurrent I_{ph} depends on the solar radiation and the cell temperature as follows:

At the open circuit point on the I-V curve, $V=V_{oc}$, I=0. Also at short circuit point on the I-V curve $I_{ph}=I_{sc}$. After substituting these values in (1) the expression for I_o at STC

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can be obtained.

$$I_{or} = \frac{I_{scr}}{\exp\left(\frac{q \cdot V_{ocr}}{AkT_r}\right) - \exp\left(\frac{q \cdot I_{scr} R_s}{AkT_r}\right)} \quad (4)$$

Where, I_{scr}, V_{ocr} are given in the datasheet at STC. The I_{sc} is proportional to the intensity of irradiance, thus I_{ph} at subjected G and T is given by

$$I_{sc} = I_{scr} \cdot \left[1 + K_i \cdot \left(T - T_r\right)\right] \cdot \frac{G}{1000}. \quad (5)$$

Where, K_i is the temperature coefficient of I_{sc} in percent change per degree temperature also given in the datasheet. Since I_o varies with temperature thus can be calculated from (3). Similarly I_{sc} from (5). I_{ph} at subjected G and T is given by

$$I_{ph} = I_{sc} + I_o\left[\exp\left(\frac{q \cdot I_{sc} R_s}{AkT}\right) - 1\right]. \quad (6)$$

The PV array power *P* can be calculated using (1) as follows:

$$P = IV = I_{ph}V - I_o V\left[\exp\left(\frac{q \cdot \left(V + IR_s\right)}{AkT}\right) - 1\right] \quad (7)$$

From which the MPOP voltage V_{mpp} can be calculated by setting $dP/dV = 0$; thus at the MPOP

$$\frac{dP}{dV} = \exp\left(\frac{q \cdot \left(V_{mpp} + I_{ph}R_s\right)}{AkT}\right) \cdot \left[\left(\frac{qV_{mpp}}{AkT}\right) + 1\right] - \frac{I_{ph} + I_o}{I_o} = 0. \quad (8)$$

Approximate value of A at STC on MPOP is given by

$$\frac{\exp\left(\frac{q \cdot \left(V_{mppr} + I_{mppr}R_s\right)}{AkT_r}\right) - \exp\left(\frac{q \cdot I_{scr}R_s}{AkT_r}\right)}{\exp\left(\frac{q \cdot V_{ocr}}{AkT_r}\right) - \exp\left(\frac{q \cdot I_{scr}R_s}{AkT_r}\right)} = \frac{I_{scr} - I_{mppr}}{I_{scr}}. \quad (9)$$

V_{mppr}, I_{mppr} and I_{scr} is given in datasheet of PV cells/Panel. Solving (8) and (9) using numerical methods, V_{mpp} and A can be calculated.

Finally, the equation of *I-V* characteristics was solved using the Newton's method for rapid convergence of the answer, because the solution of current is recursive by inclusion of a series resistance in the model [21]. The Newton's method is described as:

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \quad (10)$$

Where: $f'(x)$ is the derivative of the function, $f(x) = 0$, x_n is a present value and x_{n+1} is a next value.

$$f(I) = -I + I_{ph} - I_o\left\{\exp\left[\frac{q \cdot \left(V + IR_s\right)}{AkT}\right] - 1\right\} = 0 \quad (11)$$

By using the above equations the following output current (*I*) is computed iteratively.

$$I_{n+1} = I_n - \frac{I_{ph} - I_n - I_o\left\{\exp\left[\frac{q \cdot \left(V + IR_s\right)}{AkT}\right] - 1\right\}}{-1 - I_o\left(\frac{q \cdot R_s}{AkT}\right)\left\{\exp\left[\frac{q \cdot \left(V + IR_s\right)}{AkT}\right]\right\}} \quad (12)$$

By making step variations in the solar radiation 'G' and the cell temperature 'T' in (1-4), the I-V characterstics of the PV array can be simulated as shown in Fig. 4 and 5. Simulation of the PV array provides a flexible means of analyzing and comparing the MPOP when operated under randomly varying solar radiation and cell temperature. All of the constants in the above equations can be determined by examining the manufacturers ratings of the PV array, and then the published or measured I-V curves of the array. As a typical example, the Sunpower A300 was used to illustrate and verify the model.

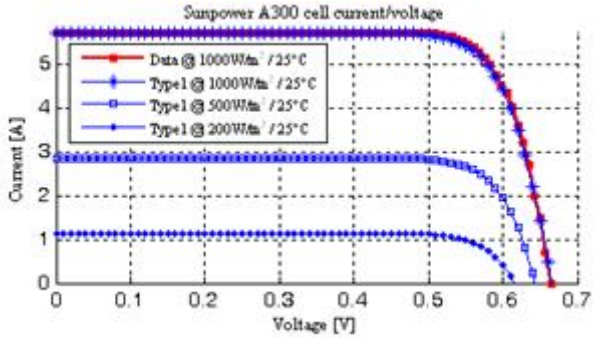

Figure 4. I-V curves of SunpowerA300Cell at various irradiance

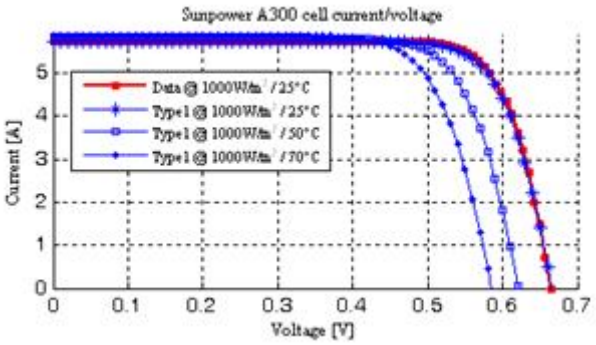

Figure 5. I-V curves of SunpowerA300Cell at various Temperatures

The open circuit voltage corresponds to the voltage drop across the diode when it was traversed by the photocurrent I_{ph}, which is equal to I_{sc}, when the generated current is I=0. It can be solved for V_{oc}

$$Voc = \frac{AkT_r}{q}\ln\left(\frac{I_{ph}}{I_o} + 1\right) = V_t \ln\left(\frac{I_{ph}}{I_o} + 1\right) \quad (13)$$

Where, V_t – thermal voltage (V)

Change of cell temperature with ambient temperature can be expressed by the following linearity

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$$T = T_a + \frac{(NOCT - 20)}{800} G. \quad (14)$$

Solar radiation was the first and temperature was the second most important effect. So, this study examined these important effecting parameters. Typically voltage decreases with increasing temperature, and current increases (although slightly), the combined effect being that power decreases. For instance; a polycrystalline module operating typically at 45 °C will therefore produce roughly 10% less power than predicted by its nominal standard test conditions rating.
The series resistance (R_s) of the PV module has a large impact on the slope of the *I-V* curve near the open-circuit voltage (V_{oc}),

C. Type-2 PV Model

The equations, which describe the I-V characteristics of the cell modeled for Type-3, are

$$I = I_{ph} - I_o \left\{ \exp\left[\frac{q \cdot (V + IR_s)}{AkT} \right] - 1 \right\} - \frac{V + IR_s}{R_p} . \quad (15)$$

R_s has a very marked effect upon the slope of the I-V curve at $V=V_{oc}$. The value of R_s was calculated by evaluating the slope dI/dV of the I-V curve at the Voc. The equation for R_s was derived by differentiating the I-V equation and then rearranging it in terms of R_s in (15).

$$R_s = -\left| \frac{dV}{dI} \right|_{V_{oc}} - \frac{1 + \frac{R_s}{R_p}}{\frac{1}{\frac{q \cdot I_o}{AkT} \exp\left(\frac{qV_{oc}}{AkT} \right)} + \frac{1}{R_p}} \quad (16)$$

Examination of (16) shows that in the adjacent of V_{oc} the $1/R_p$ may be neglecting. Therefore the final equation for R_s is same as (2). R_p, however, has an effect upon the lateral position of the MPP together with a less marked effect upon the slope of the curve at V=0, $I=I_{sc}$. The value of R_p is calculated by evaluating the slope dI/dV of the I-V curve at the I_{sc}. The equation for R_p is derived by differentiating the I-V equation and then rearranging it in terms of R_p in (16).

$$R_p = -\frac{1}{\frac{1}{\left(\left| \frac{dV}{dI} \right|_{I_{sc}} + R_s \right)} + \frac{1}{\frac{q \cdot I_o}{AkT} \exp\left(\frac{q \cdot I_{sc} R_s}{AkT} \right)}} \quad (17)$$

At the open circuit point on the IV curve, $V=V_{oc}$, I=0. Also at short circuit point on the IV curve $I_{ph}=I_{sc}$. After substituting these values in the (15) the expression for I_o at STC can be obtained.

$$I_{or} = \frac{I_{scr} - \frac{V_{oc} - I_{scr} R_s}{R_p}}{\exp\left(\frac{q \cdot V_{ocr}}{AkT_r} \right) - \exp\left(\frac{q \cdot I_{scr} R_s}{AkT_r} \right)} \quad (18)$$

Since I_o varies with temperature thus can be calculated from (3). Similarly I_{sc} from (5). I_{ph} at subjected G and T is given by

$$I_{ph} = I_{sc} + I_o \left[\exp\left(\frac{q \cdot I_{sc} R_s}{AkT} \right) - 1 \right] + \frac{I_{sc} R_s}{R_p} . \quad (19)$$

The PV array power *P* can be calculated using (15) as follows:

$$P = IV = I_{ph} V - I_o V \left[\exp\left(\frac{q \cdot (V + IR_s)}{AkT} \right) - 1 \right] \quad (20)$$

From which the MPOP voltage V_{mpp} can be calculated by setting $dP/dV = 0$; thus at the MPOP

$$\frac{dP}{dV} = \exp\left(\frac{q \cdot (V_{mpp} + I_{ph} R_s)}{AkT} \right) \cdot \left[\left(\frac{qV_{mpp}}{AkT} \right) + 1 \right] + \frac{2 \cdot V_{mpp} + I_{ph} R_s}{I_o R_p} - \frac{I_{ph} + I_o}{I_o} = 0 \quad (21)$$

Approximate value of A at STC on MPOP is given by

$$\frac{\exp\left(\frac{q \cdot (V_{mppr} + I_{mppr} R_s)}{AkT_r} \right) - \exp\left(\frac{qI_{scr} R_s}{AkT_r} \right)}{\exp\left(\frac{qV_{ocr}}{AkT_r} \right) - \exp\left(\frac{qI_{scr} R_s}{AkT_r} \right)} = \frac{I_{scr} - I_{mppr} + \frac{I_{scr} R_s}{R_p} - \frac{V_{mppr} - I_{mppr} R_s}{R_p}}{I_{scr} - \frac{V_{ocr} + I_{scr} R_s}{R_p}} \quad (22)$$

V_{mppr}, I_{mppr} and I_{scr} is given in datasheet of PV cells/Panel. Solving (21) and (22) using numerical methods, V_{mpp} and A can be calculated.
From (10), current (*I*) is computed iteratively.

$$I_{n+1} = I_n - \frac{I_{ph} - I_n - I_o \left\{ \exp\left[\frac{q \cdot (V + IR_s)}{AkT} \right] - 1 \right\} - \frac{V + IR_s}{R_p}}{-1 - I_o \left(\frac{q \cdot R_s}{AkT} \right) \left\{ \exp\left[\frac{q \cdot (V + IR_s)}{AkT} \right] - \frac{R_s}{R_p} \right\}} \quad (23)$$

D. Type 3 PV Model

The single diode models were based on the assumption that the recombination loss in the depletion region is absent. In a real solar cell, the recombination represents a substantial loss, especially at low voltages. This cannot be adequately modeled using a single diode.

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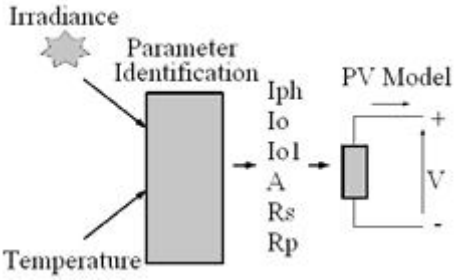

Figure 6. Modeling of Double diode PV cell

Consideration of this loss leads to a more precise model known as the two-diode model [22-25]. The equation, which describe the I-V characteristics of the cell modeled for Type 3, is

$$I = I_{ph} - I_{or}\left\{\exp\left[\frac{q\cdot(V+IR_s)}{AkT}\right]-1\right\} - I_{or1}\left\{\exp\left[\frac{q\cdot(V+IR_s)}{AkT}\right]-1\right\} - \frac{V+IR_s}{R_p} \quad (24)$$

Where, I_{ph}: the photo generated current; I_o: the dark saturation current; I_{or}: saturation current due to diffusion; I_{or1}: is the saturation current due to recombination in the space charge layer; I_{Rp}: current flowing in the shunt resistance; R_s: cell series resistance; R_p: the cell (shunt) resistance.

Furthermore, the parameters (I_{ph}, I_{or}, I_{or1} R_s, R_{sh} and A) vary with temperature, irradiance and depend on manufacturing tolerance as shown in Fig. 6. Numerical methods and curve fitting can also be used to estimate them [26-30].

IV. Simulation Result

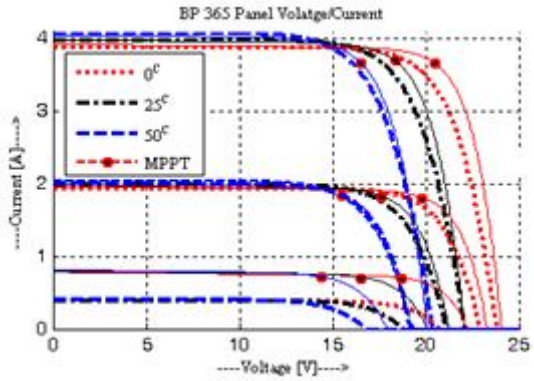

Figure 7. I-V curves for BP365 modules at different 'G' and 'T'

Table I. Parameters for the proposed models

Parameter at STC	Mono-Crystalline		m-Si	CIGS
	SPA300	SPA318	BP 365	PAE SE15
P_{max} (W)	3	318	65	15
I_{sc} (A)	5.75	6.20	3.99	1.05
V_{oc} (V)	0.665	64.7	21.1	28
I_{mpp} (A)	5.35	5.82	3.69	0.81
V_{mpp} (V)	0.560	54.7	17.6	18.56
K_v (mV/°C)	-1.9	-176.6	-80	-168
K_p (% / °C)	-0.38	-0.38	-0.5	-0.66
K_i (mA/ °C)	3.5	3.5	2.59	0.168
NOCT (°C)	45±2	45±2	47± 2	44.5
N_s	--	96	36	48

Table II. Parameters used in models

Parameter	Mono-Crystalline A300			Mono-Crystalline A318		
	T-1	T-2	T-3	T-1	T-2	T-3
R_s (Ω)	0.015	0.015	0.015	5.4	5.4	5.4
R_p (Ω)	--	300	300	--	11400	11400
A	1.2	1.2	1		1.2	1
A_1	--	--	2	--	--	2
I_{or} (A)	4e-10	4e-10	4e-10			4e-10
I_{or1} (A)	--	--	4e-10	--	--	4e-10
Eg (ev)	1.12	1.12	1.12	1.12	1.12	1.12

Table III. Parameters used in models

Parameter	Multi-Crystalline			Thin-Film		
	T-1	T-2	T-3	T-1	T-2	T-3
R_s (Ω)	0.1	0.1	0.1	10	10	10
R_p (Ω)	--		400	--	380	380
A	1.3		1	1.5	1.5	1
A_1	--	--	2	--	--	2
I_{or} (A)	8e-10	6e-10	6e-10	9e-10	9e-10	9e-10
I_{or1} (A)	--	--	6e-10	--	--	9e-10
Eg (eV)	1.14	1.14	1.14	1.38	1.38	1.38

The two diode model described in this paper was validated by the measured parameters of selected PV modules. Four modules of different brands/models were utilized for verification; these include the multi- and mono-crystalline as well as the thin-film types. The specifications of the modules are summarized in Table I. The computational results are compared with the Rs and Rp models. Note that these two models are shown in Fig. 1 and 2, respectively. Table II. and III. shows the parameters of the proposed two-diode model. Fig. 7 shows the I-V curves for BP365 modules at different G (0.2,0.5 and 1kW/m^2) and T(0,25 and 50°C)

V. Photovoltaic Module Modeling

Module is generally consisting of series and parallel combination of PV cells. Once the I-V or P-V characteristics of individual cells are known then it can easily calculated for whole module [31-33]. As shown in Fig. 8.

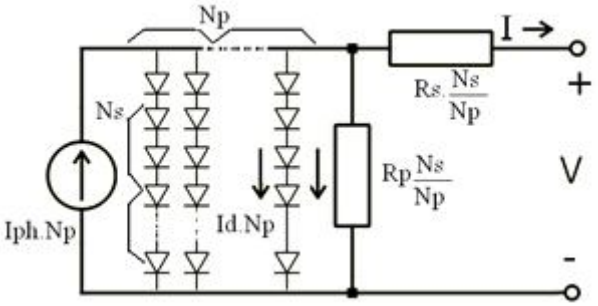

Figure 8. Module consist of series parallel combination of cells

Conclusions

In this paper, a MATLAB Simulink PV system simulator based on an improved two-diode model is proposed. To reduce the computational time, the input parameters were reduced to four and the values of Rp and Rs were estimated by an efficient iteration method. The general model was implemented on MATLAB script file, and accepts irradiance and temperature as variable parameters and outputs the I-V characteristic. Furthermore the input information to simulator

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was available on standard PV module datasheets. The simulation of large array can be interfaced with MPPT algorithm in digital domain [34]. The accurateness of the simulator is verified with four PV modules of different types (multi-crystalline, mono-crystalline and thin-film) from various manufacturers. It is observed that the two-diode model is superior to the Rp and Rs models. The results are found to be in close agreement with the theoretical predictions.

APPENDIX

I&V	Cell output current and voltage
AM	Air Mass ratio
I_{ph}	Photon or light generated current
I_o	PN junction saturation current
q	Electronic charge
A	Ideality factor
k	Boltzman's constant
R_s	Series resistance
Rp	Shunt resistance
T	Operating cell temperature
I_{scr}	Short circuit current at STC
K_i	Short ckt. current temperature coefficient at ISCR
G	Solar Insolation in W/m^2-.
STC	Standered Test Condition, T=25, AM=1.5, G=1
Tr	Reference temperature at STC
Eg	Forbidden gap
FF	Fill Factor
N_p	No. of parallel connected cells
N_s	No. of series connected cells
NOCT	Normal operating cell temperature.
MPOP	Maximum power operating point

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